On the quest for impartiality: Design and analysis of a fair non-repudiation protocol

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Abstract

We design and analyze a simple optimistic fair non-repudiation protocol. Our protocol is considerably simpler and more efficient than current proposals, due mainly to the avoidance of using session labels. We model-check both safety and liveness properties. We verify the safety properties using a standard intruder, and the liveness properties using an intruder that respects the resilient communication channels assumption. Finally, to provide further confidence in the protocol we expose several vulnerabilities on weaker versions of our protocol.

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1 Introduction

During the last decades the use of open networks for exchanging information has undergone an impressive growth. As a consequence, new security issues like *non-repudiation* and *fair exchange* have to be considered. Repudiation is the denial of a previously uttered statement or performed action. In the situation where agent A sends a message to agent B , the goal of non-repudiation guarantees that A cannot deny having sent the message and that B cannot deny having received it. One of the major difficulties in designing non-repudiation protocols is to achieve fairness, i.e. to avoid that one of the entities gets its evidence without the other one being able to get its evidence as well.

It has been shown that achieving fair exchange is impossible without a trusted third party (TTP) [16]. However, using a TTP in every exchange is inefficient. So, to avoid bottlenecks, Asokan et al. [2] introduced the optimistic approach to fair exchange, where the TTP is used *only* in the case of session recovery or abortion (which are assumed to be infrequent).

In comparison to other security issues like secrecy or authentication, fairness has not been studied intensively. Secrecy and authentication are safety properties for which the Dolev-Yao intruder has been shown to be the most powerful intruder [6]. However, we also aim at verifying (session) termination, a liveness property that cannot be verified using the standard Dolev-Yao model. Therefore, we use a modified Dolev-Yao intruder that respects the resilient communication channels assumption (saying that messages sent over the network will eventually be delivered) [5].

In the literature, several fair non-repudiation protocols have been proposed, e.g. [12, 18, 11]. These protocols use *session labels* to identify session runs. A session label typically consist of a hash of all message components. However, using session labels does not only add computational cost, but also it may introduce vulnerabilities, as shown in [11] (see Section 5).

In this paper we design an optimistic non-repudiation protocol which avoids using session labels altogether, and use a model checker to verify it. We refer the interested reader to [5] for detailed explanations regarding the adopted analysis technique and its comparison to other analysis approaches in the literature.

Contributions Our contributions are threefold, as listed below.

- We propose a fair non-repudiation protocol which is simpler than existing ones. Existing fair non-repudiation protocols use labels to identify the session runs. Here we show that these labels can be avoided, allowing for a more efficient protocol. Our TTP distinguishes session runs by recognizing fresh keys, which the TTP receives in abort or resolve requests.
- We model check our protocol using the technique of [5], briefly presented in Section 3. Our verification ensures that an honest agent (that follows the protocol) will not be treated in an unfair way, even if the agent communicates with a dishonest agent that does not follow the protocol.
- To further validate the analysis method, we illustrate several vulnerabilities found by the model-checker when different fields are missing from our protocol. This also provides confidence in the full protocol and indicates that the fields are indeed needed.

The rest of the paper is organized as follows. In the next section we describe our fair non-repudiation protocol. The intruder model and the formal analysis are described in Section 3. In Section 4 the results from the formal analysis are presented. We conclude by mentioning some related work and giving some final remarks in Section 5.

2 A fair non-repudiation protocol

In this section we describe our fair non-repudiation protocol. We first describe the underlying cryptographic assumptions and requirements on the trusted third party (TTP). Then we present our protocol, and finally we describe the evidences each party obtains and the fair exchange properties the protocol satisfies.

Cryptographic assumptions In our analysis the cryptographic operations are assumed to be “ideal”, as in Dolev and Yao [7]: First, we assume to have a secure one way hash function h . Also, we have symmetric encryption of a message M with key K , denoted by $\{M\}_K$. In $\{M\}_K$, M can only be extracted using K , and we assume that the success or failure of such a decryption is evident to the principal who performs it (this can be achieved by adding enough redundancy to M). We let $\{K\}_{TTP}$ denote K encrypted asymmetrically using the trusted third party TTP 's public key. Finally, $(X)_A$ denotes X signed by A (using A 's private key). The signature can be verified using A 's public key, and X can be extracted.

TTP assumptions Our TTP is assumed to have a persistent database of aborted or resolved sessions. This database contains entries of the form $\langle status : X \ Y \ W \ Z \rangle$. In our protocol, *status* is either *aborted* or *resolved*; X and Y are agent identities, W is a cryptographic key and Z is the hash of a ciphertext. A *query* to this database is denoted by a predicate $status(X, Y, W, Z)$, which holds when entry $\langle status : X, Y, W, Z \rangle$ exists in the TTP's database.

2.1 Protocol

The non-repudiation protocol that we present below allows an agent A to send a message M to agent B in a *fair* manner, meaning that A gets *evidence of receipt* (EOR) iff B receives M as well as *evidence of origin* (EOO). The EOR allows A to prove that B did indeed receive M , while the EOO allows B to prove that it was A who sent M . We describe the verification of this in Section 3. The protocol consists of three sub-protocols:

Main protocol The agent A wants to send M to B , using TTP for session abort or resolution. Before the first message, A chooses a fresh key K . The main protocol is then:

1. $A \rightarrow B : \{M\}_K, EOO_M$ where $EOO_M = (B, TTP, h(\{M\}_K), \{K, A\}_{TTP})_A$
2. $B \rightarrow A : EOR_M$ where $EOR_M = (EOO_M)_B$
3. $A \rightarrow B : K$
4. $B \rightarrow A : EOR_K$ where $EOR_K = (A, h(\{M\}_K), K)_B$

First A sends $\{M\}_K$, along with EOO_M , which consists of B and TTP 's identities, a commitment to send M using K in the form of a hash $h(\{M\}_K)$, and K encrypted with the TTP 's public key (along with A 's identity) in case the session is later resolved.

On receipt, B stores $\{M\}_K$, checks the signature of EOO_M to ensure that the message is genuinely coming from A , and extracts the values for performing more tests: Firstly, it checks that the leftmost value of EOO_M is B 's identity; Secondly, that TTP is a valid TTP for B , whom B trusts for recovering a session; Thirdly, B checks that the included hash commitment is indeed the hash of $\{M\}_K$. When all this is verified, B signs EOO_M with his private key to obtain EOR_M and sends it to A .

When A gets this message, it checks whether the signature is that of B . If this is the case, A sends K to B . When B receives K , it checks that K decrypts $\{M\}_K$ correctly (B can verify that the result of the decryption is successful). If so, B sends EOR_K , signing K along with A 's identity and $h(\{M\}_K)$.

Abort protocol If A does not receive a valid EOR_M from B , at step 2 in the main protocol, then A can invoke the *abort* protocol, for canceling the exchange:

1. $A \rightarrow TTP: (abort, h(\{M\}_K), B, \{K, A\}_{TTP})_A$
2. $TTP \rightarrow A: \begin{cases} E_{TTP} \text{ where } E_{TTP} = (A, B, K, h(\{M\}_K))_{TTP}, \\ \quad \text{if } resolved(A, B, K, h(\{M\}_K)) \\ AB_{TTP} \text{ where } AB_{TTP} = (A, B, h(\{M\}_K), \{K, A\}_{TTP})_{TTP}, \\ \quad \text{otherwise} \end{cases}$

First A sends to TTP an *abort request* message consisting of an *abort* flag, the commitment $h(\{M\}_K)$, B 's identity and $\{K, A\}_{TTP}$.

On receipt, TTP checks A 's signature, and checks that it can decrypt the message $\{K, A\}_{TTP}$. If the decryption succeeds, TTP checks that the included identity A next to the key K matches the signature of the whole abort request message. If also this succeeds, TTP queries its database with $resolved(A, B, K, h(\{M\}_K))$. If the query holds, it means that this session has been resolved earlier. The answer from TTP to A is then E_{TTP} , including the key K signed by the private key of TTP . In the case that query fails, TTP declares that the session is aborted and stores the entry $\langle aborted, A, B, K, h(\{M\}_K) \rangle$ in its database. The answer AB_{TTP} signed by the TTP is returned to A , as an acknowledgment of the successful abortion. Note that this message does not include K in the clear.

Resolve protocol If B does not get K or A does not get EOR_K , then both parties may *resolve* the protocol by consulting TTP :

1. $P \rightarrow TTP: ((B, TTP, h(\{M\}_K), \{K, A\}_{TTP})_A)_B$
2. $TTP \rightarrow P: \begin{cases} AB_{TTP}, \\ \quad \text{if } aborted(A, B, K, h(\{M\}_K)) \\ E_{TTP}, \\ \quad \text{otherwise} \end{cases}$

Here, P is the party that is resolving the session (i.e. A or B). First P sends EOR_M , as a *resolve request* message. On receipt, TTP checks the validity of the signatures, and the successful decryption and matching of $\{K, A\}_{TTP}$. Then, TTP queries its database for $aborted(A, B, K, h(\{M\}_K))$ to find out whether the session has been previously aborted. If the session has not been aborted, the resolve request is accepted, and TTP proceeds by storing $\langle resolved, A, B, K, h(\{M\}_K) \rangle$ in its database, and answers with E_{TTP} evidence containing key K , which is signed with TTP 's private key. If the session is already aborted, TTP answers with AB_{TTP} , a message representing the fact that the session has already been aborted.

2.2 Evidences and dispute resolution

In case of a dispute, the parties may present their evidences to an external judge. In the protocol presented above, the evidence of receipt EOR for A is EOR_M and $\{M\}_K$, plus either EOR_K or E_{TTP} . The evidence of origin EOO for B is EOO_M , $\{M\}_K$ and K .

Dispute resolution Suppose B claims that it did not receive M from A , when A possesses EOR. Then A presents EOR_M , $\{M\}_K$ and either EOR_K or E_{TTP} to the judge. The messages EOR_M and $\{M\}_K$ provide proof that B committed in the session to receive M ,

while EOR_K or E_{TTP} represent that either B received K , or he can receive it from TTP , respectively.

Suppose A claims that it did not send M to B , when B possesses EOO. Then B presents EOO_M , $\{M\}_K$ and K to the judge, who can check that A had indeed committed to communicate M to B . Since K was freshly created by A , B could only have received it from A directly or from TTP , who checked that A provided the correct K in EOO_M .

2.3 Fair exchange properties

We aim at verifying *effectiveness*, *fairness* and *timeliness* (cf. requirements for fair exchange in [1]). These properties are illustrated in the case where A is the initiator and B the responder:

- Effectiveness says that if A and B behave according to the protocol and A does not abort, then the protocol session will reach a state where B has received the message M and EOO, and A has received EOR, and both A and B *terminate*, i.e. have no further pending operations to perform in that protocol session.
- Fairness expresses that when the protocol session has terminated then B has received M and EOO if and only if A has received EOR.
- Timeliness means that protocol sessions terminate for all honest parties. In other words, after an honest agent X has initiated a protocol session with some Y , then X will reach its termination¹. Moreover, timeliness also specifies that *after* this termination the *degree of fairness* does not decrease for X : if X did not get his evidence before termination then it cannot be that Y gets her evidence without X also getting his.

Effectiveness is a sanity check for the functionality of the protocol, and may thus be verified in a system without intruder. For the other two properties, we can first verify termination and then check fairness and timeliness assuming that the protocol sessions terminate. This has the benefit of reducing the two properties to safety properties. Thus, termination is the only *liveness* property that needs to be checked.

3 Formal analysis

We now turn to implementing the necessary machinery to formally analyze whether the protocol that we propose in Section 2.1 meets the properties described in Section 2.3.

3.1 Communication model

We consider two different communication models. The first model is used for verifying effectiveness. In this model there is no intruder (all agents are honest): A set of agents communicate over a network, performing send and receive actions. These actions are synchronized, meaning that an agent A can only send a message m to B (denoted by $send(A, m, B)$), if B at the same time receives it from A (denoted by $recv(A, m, B)$). The synchronization between $send(A, m, B)$ and $recv(A, m, B)$ actions is denoted by $com(A, m, B)$.

We use a second model to verify all the remaining properties. In this model there is an intruder I with complete control over the network. When an agent A sends a message m with the intention that it should be received by B , it is in fact the intruder that receives it, and it is also only from the intruder that B may receive m . Also in this model send and receive actions are synchronized.

¹Here termination refers to that particular agents' session. An agent X may continue executing subsequent sessions after one session is finished.

3.2 The μ CRL specification language

Here we briefly describe the symbols used in the pseudo code of the intruders below. For a complete description of the syntax and semantics of μ CRL we refer to [10].

The symbols ‘.’ and ‘+’ are used for the sequential and alternative composition (“choice”) operator, respectively. The operator $\sum_{d \in D} P(d)$ behaves like $P(d_1) + P(d_2) + \dots$. The process expression $p \triangleleft b \triangleright q$, where b is a term of sort **bool** and p and q are processes, behaves like p if b is true, and like q if b is false. Finally, τ represents an internal action, and the constant δ expresses that, from then on, no action can be performed.

3.3 Intruder models

We use two different intruder models. For safety properties the normal Dolev-Yao intruder [7] is used. As mentioned earlier, this intruder is not suitable for verification of liveness properties [15], so to verify termination we use the intruder suggested in [5]. This intruder is shown to be equivalent, w.r.t. termination, to the Dolev-Yao intruder that respects the resilient communication channels assumption (RCC, messages sent over the network will eventually be delivered) [5], which is enough for our purposes.

The Dolev-Yao intruder stores all received messages in a set X , representing its knowledge. The intruder uses X for synthesizing new messages (*synth* in the pseudo code below), using the usual rules of message (de)composition (in particular, the intruder can decrypt and sign messages only if it knows the corresponding key). The intruder can also block communications.

Below we illustrate a specification of an intruder DY_B , in this case played by dishonest agent B . The intruder DY_B can perform a special evidence action $evidence_B(k, m)$. This action is parameterized by a key k and a message m , meaning that the gathered evidence regards message m and was provided in the session using key k . We allow DY_B to perform the action $evidence_B(k, m)$ only when it can synthesize $EOO(k, m)$. In general, the particular data that constitutes an evidence is protocol specific, denoted below by $EOO(k, m)$.

$$\begin{aligned}
 DY_B(X) = & \sum_{\substack{p \in Agent \\ m \in Message}} recv(p, m, B).DY_B(X \cup \{m\}) + \\
 & \sum_{\substack{p \in Agent \\ synth(m, X)}} send(B, m, p).DY_B(X) + \\
 & \sum_{\substack{k \in Key \\ m \in msg \\ \tau. \delta}} evidence_B(k, m).DY_B(X) \triangleleft synth(EOO(k, m)) \triangleright \delta +
 \end{aligned}$$

According to the bisimulation semantics that underlies μ CRL, a process $p + \delta$ behaves like p . So to express that the intruder shall be able to stop all communications at its own will, we let it perform an internal action τ before deadlock δ .

The intruder I_B for verifying termination maintains another set Y of knowledge (besides X), for messages that have been received but not yet sent (cf. RCC). For distinguishing the send actions that the intruder eventually has to perform (according to RCC) from the ones that it can perform (but does not have to), the send actions are tagged with X and Y , respectively. The synchronizations between send and receive actions are denoted *com*, *com_X* and *com_Y* referring to the synchronizations between *send* and *recv*, *send_X* and *recv*, and *send_Y* and *recv*, respectively.

$$\begin{aligned}
I_B(X, Y) = & \sum_{\substack{p \in Agent \\ m \in Message}} recv(p, m, B).I_B(X \cup \{m\}, Y \cup \{m\}) + \\
& \sum_{\substack{p \in Agent \\ m \notin Y \\ synth(m, X)}} send_X(B, m, p).I_B(X, Y) + \\
& \sum_{\substack{p \in Agent \\ m \in Y}} send_Y(B, m, p).I_B(X, Y \setminus \{m\})
\end{aligned}$$

Note that when we split the fairness and timeliness properties into termination and two safety properties, as described in Section 2.3, we also verify these properties using the two different intruders above. This can be done since the intruder I is equivalent to the Dolev-Yao intruder that respects the communication channels assumption [5].

3.4 The μ CRL toolset

The formalization of the protocol described in Section 2 is carried out in μ CRL [10]. The μ CRL toolset includes an automatic state space generator and symbolic state space reduction tools. The fair exchange properties are expressed in the regular alternation-free μ -calculus [14]. The model checker EVALUATOR 3.0 [14] from the CADP tool set [8] is then used to verify these properties.

3.5 Regular alternation-free μ -calculus

The regular alternation-free μ -calculus is used here to formulate properties of (states in) labeled transition systems. It is a fragment of μ -calculus that can be efficiently checked. Here we briefly describe what is needed for expressing the fair exchange properties of the protocol we investigate. For a complete description of the syntax and semantics we refer to [14]. The regular alternation-free μ -calculus is built up from three types of formulas: *action formulas*, *regular formulas* and *state formulas*. We use ‘.’, ‘ $\vee$ ’, ‘ $\neg$ ’ and ‘*’ for concatenation, choice, complement and transitive-reflexive closure, respectively, of regular formulas. The symbols F and T are used in both action formulas and state formulas. In action formulas they represent *no action* and *any action*, respectively. The meaning of F and T in state formulas are the empty set and the entire state space, respectively. The operators $\langle \dots \rangle$ and $[\dots]$ have their usual meaning ($\Diamond$ and $\Box$ in modal logics). The CADP toolset also allows wildcards in action parameters. These are represented with ‘*’.

3.6 The fair exchange properties

Here we formalize the fair exchange properties that we verify. To enhance readability, the protocol implementations protocols are extended with certain *abstract* actions that do not affect the behavior of the agents. An agent P performs the actions $init_P(k, m)$ when it engages in a protocol session, $terminate_P(k, m)$ when the session is over from P ’s point of view, and $evidence_P(k, m)$ when it receives a valid evidence, for the key k and item m . The trusted third party TTP performs $abort(k, m)$ when a session is successfully aborted, for the key k and item m . For a more precise description of exactly when these actions are performed, we include the μ CRL code of the protocol in the Appendix.

First, we check that the protocol is effective. Note that this is verified in the model without intruder. Whenever agent P has started execution, then P ’s termination is inevitable:

$$[T^*.init_P(k, m)]\mu X(\langle T \rangle T \wedge [\neg terminate_P(k, m)] X) \quad (1)$$

Also, if there is no abort, P receives its evidence before termination:

$$[(\neg(\text{abort}(k, m) \vee \text{evidence}_P(k, m))^*.\text{terminate}_P(k, m))]F \quad (2)$$

Now we turn to the fairness and timeliness properties, to be verified in the model with intruder. We assume that the intruder plays the role of Q . The properties below are thus defined to describe “fairness for P ”. The corresponding properties for Q are defined in a similar way. The properties fairness and timeliness are verified, as described above, by verifying termination separately, using the intruder described in Section 3.3

$$[T^*.\text{init}_P(k, m).(\neg\text{terminate}_P(k, m))^*][(\neg\text{com}_P(*, *, *))^*.\text{terminate}_P(k, m)]T, \quad (3)$$

i.e. whenever $\text{init}_P(k, m)$ has happened, but not yet $\text{terminate}_P(k, m)$, there is a path to $\text{terminate}_P(k, m)$ that does not contain com_P actions. This means that, whenever $\text{init}_P(k, m)$ has happened, but not yet $\text{terminate}_P(k, m)$, and assuming RCC, $\text{terminate}_P(k, m)$ will happen.

The remaining properties are safety properties and the normal Dolev-Yao intruder is used. Fairness (for P) says if Q gets its evidence, then so shall P :

$$[(\neg\text{evidence}_Q(k, m))^*.\text{evidence}_P(k, m).(\neg\text{evidence}_Q(k, m))^*.\text{terminate}_P(k, m)]F \quad (4)$$

The property above says that P cannot terminate in a state that is unfair for P . But since P actually will terminate (formula 3), P will indeed terminate in a fair state.

Finally, timeliness (for P) says that after P ’s termination, if P has not got his evidence, Q cannot get her evidence unless P initiates a new session with same key and item:

$$[(\neg\text{evidence}_P(k, m))^*.\text{terminate}_P(k, m).(\neg\text{init}_P(k, m))^*.\text{evidence}_Q(k, m)]F \quad (5)$$

In the case when P does initiate a new session with same key and item, P will get his evidence if Q gets hers (according to the properties 3 and 4).

4 Results

In this section we describe the results obtained from the formal analysis described in Section 3 performed over our protocol proposed in Section 2.

Honest scenario S_0 : A and B behave honestly We first encode a scenario in which both A and B are honest, along with the TTP. A exchanges items with B using fresh keys. To model timeouts, we use nondeterministic choices between communication actions. For instance, either A receives an answer timely from B in Message 2, in the main protocol, or it decides to initiate the abort sub-protocol. Correspondingly, B has a choice between a send action and a τ action, which models an asynchronous communication in which the message is ignored by A .

This scenario was model-checked using the CADP toolset, confirming that it is deadlock-free, and effective. For corresponding specification see A.1, and for verified properties see C.7.

Result 1 *The protocol from Section 2.1 is effective for scenario S_0 , satisfying the properties (1) and (2) from Section 3.6 with respect to agent A .*

Dishonest scenario S_1 : A dishonest, B honest When B is honest but A is dishonest, we execute B along with the intruder, who takes the identity of A .

We first verify the safety properties using the standard Dolev-Yao intruder (the first intruder in Section 3.3). We model check whether A can generate B ’s evidence in an unfair manner, and verify that this is indeed impossible. For corresponding code see A.2, and for verified properties see C.1 and C.3.

Missing A 's identity in EOO_M We now consider the case in which A 's identity is excluded from the component $\{K, A\}_{TTP}$ inside EOO_M . Suppose then that $EOO'_M = (B, TTP, h(\{M\}_K), \{K\}_{TTP})_A$. The following attack is found:

- a1. $A \rightarrow B : \{M\}_K, EOO_M$ where $EOO'_M = (B, TTP, h(\{M\}_K), \{K\}_{TTP})_A$
- b1. $B \rightarrow C : \{M\}_K, EOO_M$ where $EOO'_M = (C, TTP, h(\{M\}_K), \{K\}_{TTP})_B$
- 2. $C \rightarrow B : EOR'_M$ where $EOR'_M = (EOO'_M)_C$

When A starts a session with B , B immediately starts another session with some other agent C , reusing the information that A used. When C answers, B resolves obtaining K and therefore evidence, which A cannot obtain since B never answered to A 's first message.

We created a scenario in which B is dishonest and A is honest. Interestingly, B can simply reuse its own identity and resolve to “itself” (we disallow the TTP to check this). The analogous to Result 2 for B for this scenario is violated, confirming that the identity of A is needed inside $\{K, A\}_{TTP}$.

Missing A 's identity in EOR_K Now we consider the situation in which A 's identity is missing in EOR_K , so that $EOR_K = (h(\{M\}_K), K)_B$. The following vulnerability is found:

- a1. $A \rightarrow B : \{M\}_K, EOO_M$ where $EOO_M = (B, TTP, h(\{M\}_K), \{K, A\}_{TTP})_A$
- a2. $B \rightarrow A : EOR_M$ where $EOR_M = (EOO_M)_B$
- a3. $A \rightarrow B : K$
- a4. $B \rightarrow A : EOR_K$ where $EOR_K = (h(\{M\}_K), K)_B$
- b1. $C \rightarrow B : \{M\}_K, EOO_M$ where $EOO_M = (B, TTP, h(\{M\}_K), \{K, C\}_{TTP})_C$
- b2. $B \rightarrow C : EOR_M$ where $EOR_M = (EOO_M)_B$

Here, A runs a normal session a with B which terminates. A is allied to another user C , who starts a ‘replay’ of the session by A : we assume A hands over M and K to C . Now, B replies with EOR_M , at which point C aborts the session with B . B is then unable to obtain evidence, but C has evidence since EOR_K does not mention A nor C , and thus it constitutes valid evidence EOR for C as well. This vulnerability appears in our analysis when we hand out information to a dishonest A about previous sessions, that is we give some EOR_K to A (which may be from an old session of B with some other agent X which we assume is allied to A). In such a scenario $S_{a'}$, Result 2 is violated immediately after A runs the abort protocol, after B answers his second message. Thus, we conclude that EOR_K needs to include A 's identity as well. For the corresponding code see B.3.

Missing hash in EOR_K Finally we consider the case in which the hash $h(\{M\}_K)$ is missing in EOR_K , that is, $EOR_K = (A, K)_B$. The following attack is then possible:

- a1. $A \rightarrow B : \{M\}_K, EOO_M$ where $EOO_M = (B, TTP, h(\{M\}_K), \{K, A\}_{TTP})_A$
- a2. $B \rightarrow A : EOR_M$ where $EOR_M = (EOO_M)_B$
- a3. $A \rightarrow B : K$
- a4. $B \rightarrow A : EOR_K$ where $EOR_K = (A, K)_B$
- b1. $A \rightarrow B : \{M'\}_K, EOO_M$ where $EOO_M = (B, TTP, h(\{M'\}_K), \{K, A\}_{TTP})_A$
- b2. $B \rightarrow A : EOR_M$ where $EOR_M = (EOO_M)_B$

Similar to the previous case, A runs a normal session a with B . Then A starts another session, but now using a different message M' , reusing the same key K . After obtaining an answer from B , A aborts the session. In this state A has valid evidence since the previous EOR_K is not bound to M , and thus it is valid also for an exchange between A and B with K . One could argue that B also ‘remembers’ K and thus it can obtain M' , however B is not supposed to be stateful and save old keys. B just follows the protocol as it is indicated, and thus this constitutes a valid attack for A . For the corresponding code see B.4.

In a scenario S_d with A dishonest and B honest, Result 2 is quickly violated, exposing the above vulnerability and confirming that indeed EOR_K needs to include $h(\{M\}_K)$.

5 Conclusions, further and related work

We present a novel optimistic non-repudiation protocol, simpler than previous proposals. The simplicity is due to avoiding the usage of labels to identify sessions and assuming the usage of fresh keys per-session. We model-check the proposed protocol and verify the fair exchange properties using the technique in [5]. To provide further confidence in our proposal we illustrate vulnerabilities when different fields are missing in the protocol.

It would be interesting to apply the verification technique to model other proposed protocols (e.g. see below in Related Work), and confirm known vulnerabilities.

Related Work. Several non-repudiation protocols have been defined earlier. Among the simplest ones we find the three-round protocol proposed by Gomila and Rotger [9]. Unfortunately, three messages do not seem to be enough to achieve fair exchange properly, as shown by Boyd and Kearney [4]. More recently, Kremer and Markowitch [12] proposed a four-message protocol (KM) to achieve non-repudiation. Their protocol is analyzed by Kremer and Raskin [13] using a game-based technique. Quite similar to the KM protocol is Zhou-Gollman's protocol (ZG) [18]. Still, the small differences between the two protocols provide interesting analysis scenarios of potential unfair situations. Vogt et al. [11] present several potential unfair situations that may happen in both the KM² and ZG protocols. Vogt et al. show that these unfair situations arise from confusion in the *labels* used to identify the session runs. By carefully setting complex labels, Vogt et al. propose a protocol for achieving fair exchange. The ZG protocol was also analyzed by Bella and Paulson [3] who used the theorem prover Isabelle to model a non-repudiation protocol by an inductive definition and to prove some desired properties. Another interesting approach to formal verification of fair exchange is the work by Shmatikov and Mitchell [17] who used the model checker Mur ϕ to analyze fair exchange and contract signing protocols, using a Dolev-Yao intruder.

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²The KM protocol was not originally designed to provide fair exchange but simply non-repudiation (private communication, 2004).

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Appendix

A Protocol spec in μ CRL

A.1 Honest protocol runs

```
% Abstract Data Types
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Bool Data Type
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sort      Bool
func      T,F: -> Bool
map       and,or: Bool # Bool -> Bool
          not: Bool -> Bool
          eq: Bool # Bool -> Bool
          leq: Bool # Bool -> Bool
          if: Bool # Bool # Bool -> Bool
var       x,x': Bool
rew       and(T,T)=T
          and(F,x)=F
          and(x,F)=F
          or(T,x)=T
          or(x,T)=T
          or(F,F)=F
          not(F)=T
          not(T)=F
          leq(x,x)=T
          leq(F,x)=T
          leq(T,F)=F
          eq(x,x')=and(leq(x,x'),leq(x',x))
          if(T,x,x')=x
          if(F,x,x')=x'

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Key Data Type
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sort      Key
func      zero :-> Key
          % one:-> Key
          ttp :-> Key
map       eq:Key#Key->Bool
          leq:Key#Key->Bool
          nxt:Key->Key
var       k1,k2: Key
rew       leq(k1,k1)=T
          leq(zero,k1)=T
          leq(ttp,zero)=F
          eq(k1,k2)=and(leq(k1,k2),leq(k2,k1))
nxt(zero)=ttp
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Item Data Type.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```

sort      Item
func      d1: -> Item
map       eq: Item # Item -> Bool
          leq: Item # Item -> Bool
var       d,d': Item
rew       leq(d,d)=T
          eq(d,d')=and(leq(d,d'),leq(d',d))

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Player Data Type
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sort      Player
func      A,B,S :-> Player
map       eq : Player # Player->Bool
          leq: Player # Player->Bool
var       p,p': Player
rew       leq(p,p)=T
          leq(A,B)=T          leq(A,S)=T
          leq(B,A)=F          leq(B,S)=T
          leq(S,A)=F          leq(S,B)=F
          eq(p,p')=and(leq(p,p'),leq(p',p))

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Message Data Type
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sort      Message
func      boolm:Bool-> Message
          itm:Item->Message
          player: Player -> Message
          keym: Key -> Message
          pair: Message#Message->Message
          hash: Message->Message
          sign: Player#Message->Message
          enc: Key#Message->Message

map       eq: Message#Message->Bool
          leq: Message#Message->Bool
var       m1,m2,m3,m4: Message
          p1,p2: Player
          x,x': Bool
          d,d': Item
          k1,k2: Key
rew       eq(m1,m2)=and(leq(m1,m2),leq(m2,m1))
%definition for leq
          leq(m1,m1)=T
          leq(boolm(x), boolm(x'))=leq(x,x')
          leq(itm(d),itm(d'))=leq(d,d')
          leq(player(p1),player(p2))=leq(p1,p2)
          leq(keym(k1),keym(k2))=leq(k1,k2)
          leq(pair(m1,m2),pair(m3,m4))=if(eq(m1,m3),leq(m2,m4),leq(m1,m3))
          leq(hash(m1),hash(m2))=leq(m1,m2)
          leq(sign(p1,m1),sign(p2,m2))=if(eq(p1,p2),leq(m1,m2),leq(p1,p2))

```

$\text{leq}(\text{enc}(k1,m1), \text{enc}(k2,m2)) = \text{if}(\text{eq}(k1,k2), \text{leq}(m1,m2), \text{leq}(k1,k2))$

$\text{leq}(\text{boolm}(x), \text{itm}(d)) = T$
 $\text{leq}(\text{boolm}(x), \text{player}(p1)) = T$
 $\text{leq}(\text{boolm}(x), \text{pair}(m1,m2)) = T$
 $\text{leq}(\text{boolm}(x), \text{hash}(m1)) = T$
 $\text{leq}(\text{boolm}(x), \text{sign}(p1,m1)) = T$
 $\text{leq}(\text{boolm}(x), \text{enc}(k1,m1)) = T$
 $\text{leq}(\text{boolm}(x), \text{keym}(k1)) = T$

$\text{leq}(\text{itm}(d), \text{boolm}(x)) = F$
 $\text{leq}(\text{itm}(d), \text{player}(p1)) = T$
 $\text{leq}(\text{itm}(d), \text{pair}(m1,m2)) = T$
 $\text{leq}(\text{itm}(d), \text{hash}(m1)) = T$
 $\text{leq}(\text{itm}(d), \text{sign}(p1,m1)) = T$
 $\text{leq}(\text{itm}(d), \text{enc}(k1,m1)) = T$
 $\text{leq}(\text{itm}(d), \text{keym}(k1)) = T$

$\text{leq}(\text{player}(p1), \text{boolm}(x)) = F$
 $\text{leq}(\text{player}(p1), \text{itm}(d)) = F$
 $\text{leq}(\text{player}(p1), \text{pair}(m1,m2)) = T$
 $\text{leq}(\text{player}(p1), \text{hash}(m1)) = T$
 $\text{leq}(\text{player}(p1), \text{sign}(p2,m1)) = T$
 $\text{leq}(\text{player}(p1), \text{enc}(k1,m1)) = T$
 $\text{leq}(\text{player}(p1), \text{keym}(k1)) = T$

$\text{leq}(\text{pair}(m1,m2), \text{boolm}(x)) = F$
 $\text{leq}(\text{pair}(m1,m2), \text{itm}(d)) = F$
 $\text{leq}(\text{pair}(m1,m2), \text{player}(p1)) = F$
 $\text{leq}(\text{pair}(m1,m2), \text{hash}(m3)) = T$
 $\text{leq}(\text{pair}(m1,m2), \text{sign}(p1,m3)) = T$
 $\text{leq}(\text{pair}(m1,m2), \text{enc}(k1,m3)) = T$
 $\text{leq}(\text{pair}(m1,m2), \text{keym}(k1)) = T$

$\text{leq}(\text{hash}(m1), \text{boolm}(x)) = F$
 $\text{leq}(\text{hash}(m1), \text{itm}(d)) = F$
 $\text{leq}(\text{hash}(m1), \text{player}(p1)) = F$
 $\text{leq}(\text{hash}(m1), \text{pair}(m2,m3)) = F$
 $\text{leq}(\text{hash}(m1), \text{sign}(p1,m2)) = T$
 $\text{leq}(\text{hash}(m1), \text{enc}(k1,m2)) = T$
 $\text{leq}(\text{hash}(m1), \text{keym}(k1)) = T$

$\text{leq}(\text{sign}(p1,m1), \text{boolm}(x)) = F$
 $\text{leq}(\text{sign}(p1,m1), \text{itm}(d)) = F$
 $\text{leq}(\text{sign}(p2,m1), \text{player}(p1)) = F$
 $\text{leq}(\text{sign}(p1,m1), \text{pair}(m2,m3)) = F$
 $\text{leq}(\text{sign}(p1,m1), \text{hash}(m2)) = F$
 $\text{leq}(\text{sign}(p1,m1), \text{enc}(k1,m2)) = T$
 $\text{leq}(\text{sign}(p1,m1), \text{keym}(k1)) = T$

$\text{leq}(\text{enc}(k1,m1), \text{boolm}(x)) = F$
 $\text{leq}(\text{enc}(k1,m1), \text{itm}(d)) = F$


```

leq(enc(k1,m1), player(p1))=F
leq(enc(k1,m1), pair(m2,m3))=F
leq(enc(k1,m1), hash(m2))=F
leq(enc(k1,m1), sign(p1,m2))=F
leq(enc(k1,m1), keym(k2))=T

% The behaviour of 'refresh' function depends on this ordering
leq(keym(k1), boolm(x))=F
leq(keym(k1), itm(d))=F
leq(keym(k1), player(p1))=F
leq(keym(k1), pair(m1,m2))=F
leq(keym(k1), hash(m1))=F
leq(keym(k1), sign(p1,m1))=F
leq(keym(k1), enc(k2,m1))=F

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Set of Knowledge
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sort    Knowledge
func    emptset :-> Knowledge
map     set: Message # Knowledge -> Knowledge
        add: Message # Knowledge -> Knowledge
        union : Player # Knowledge # Knowledge -> Knowledge
        synthadd : Player# Message # Knowledge -> Knowledge
        rem: Message # Knowledge -> Knowledge
        in: Message # Knowledge -> Bool
        if: Bool # Knowledge # Knowledge -> Knowledge
        eq: Knowledge # Knowledge -> Bool
var     k, k': Knowledge
        a,a': Message
        p: Player
rew     if(T, k, k')=k
        if(F, k, k')=k'

        add(a,emptset)=set(a,emptset)
        add(a,set(a',k))=
            if(leq(a,a'),
                if(eq(a,a'),set(a',k),set(a,set(a',k))),
                set(a',add(a,k)))

        synthadd(p,a,k)=if(synth(p,a,k),k,add(a,k))

        union(p,k,emptset)=k
        union(p,emptset,k)=k
        union(p,set(a,k),k')= synthadd(p,a,union(p,k,k'))

        rem(a,emptset)=emptset
        rem(a,set(a',k))=
            if(leq(a,a'),if(eq(a,a'),k,set(a',k)),set(a',rem(a,k)))

        in(a, emptset)=F
        in(a, set(a',k))=if(leq(a,a'),eq(a,a'),in(a,k))

```

```

eq(k,k)=T
eq(emptyset,set(a,k))=F
eq(set(a,k),emptyset)=F
eq(set(a,k),set(a',k'))=and(eq(a,a'),eq(k,k'))

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
map    synth: Player # Message # Knowledge->Bool
var    k:Knowledge
        p,q:Player
        bol: Bool
        m,m': Message
        d:Item
        z:Key
rew    synth(p,boolm(bol),k)=T
        synth(p,player(q),k)=T
        synth(p,itm(d),k)=or(eq(p,A),in(itm(d),k)) %Alice knows items
        %Alice initially has keys in its knowledge set.
        synth(p,keym(z),k)=in(keym(z),k)
        synth(p,pair(m,m'),k)=and(synth(p,m,k),synth(p,m',k))
        synth(p,hash(m),k)=or(in(hash(m),k),synth(p,m,k))
        synth(p,sign(q,m),k)=or(and(eq(p,q),synth(p,m,k)),in(sign(q,m),k))
        %Alice knows all keys and ttp is a public key
        synth(p,enc(z,m),k)=
            or(in(enc(z,m),k),
                and(synth(p,m,k),or(eq(z,ttp),synth(p,keym(z),k))))
        %intruder has some unremovable knowledge
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
map    decomp: Player # Message->Knowledge
var    k:Knowledge
        p,q:Player
        bol: Bool
        m,m': Message
        d:Item
        z:Key
rew    decomp(p,boolm(bol))=emptyset
        decomp(p,player(q))=emptyset
        decomp(p,itm(d))=if(eq(p,A),emptyset,set(itm(d),emptyset))
        %Alice just needs ttp's key
        decomp(p,keym(z))=set(keym(z),emptyset)
        decomp(p,pair(m,m'))=union(p,decomp(p,m),decomp(p,m'))
        decomp(p,hash(m))=set(hash(m),emptyset)
        decomp(p,sign(q,m))=synthadd(p,sign(q,m),decomp(p,m))
        %Will be decrypted by 'refresh' function
        decomp(p,enc(z,m))=set(enc(z,m),emptyset)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Refresh function.
% The idea is to refresh the knowledge set of the intruder once
% a key is added to it.
% Assuming one layer of encryption (by inspecting the protocol),
% it is enough to apply this function once, but in general it is

```

```

% possible to recursively apply it until no more changes in the
% knowledge set is observed.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
map      refresh : Player# Knowledge -> Knowledge
var      k: Knowledge
          p,q : Player
          a,a': Message
          z: Key
          x: Bool
          d: Item
rew      refresh(p,emptset)=emptset
          refresh(p,set(boolm(x),k))=add(boolm(x),refresh(p,k))
          refresh(p,set(itm(d),k))=add(itm(d),refresh(p,k))
          refresh(p,set(player(q),k))=add(player(q),refresh(p,k))
          refresh(p,set(keym(z),k))=add(keym(z),refresh(p,k))
          refresh(p,set(pair(a,a'),k))=add(pair(a,a'),refresh(p,k))
          refresh(p,set(hash(a),k))=add(hash(a),refresh(p,k))
          refresh(p,set(sign(q,a),k))=add(sign(q,a),refresh(p,k))

          refresh(p,set(enc(z,a),k))=if(in(keym(z),k),
                                         union(p,decomp(p,a),refresh(p,k)),
                                         add(enc(z,a),refresh(p,k)))

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Process Declaration
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
act      send,recv,com:Player#Message#Player
          init_Bob,init_Alice:Key#Item
          evidence_Bob:Key#Item
abort:Key#Item
evidence_Alice:Key#Item
          terminate_Bob,terminate_Alice:Key#Item

comm     send|recv=com
proc

Bob=sum(x:Key,sum(y:Item,
  recv(A,pair(enc(x,itm(y))),
    %E00
    sign(A,pair(player(B),
      pair(player(S),
        pair(hash(enc(x,itm(y))),
          enc(ttp,pair(keym(x),
            player(A))))))))) ,B).

init_Bob(x,y).
(send(B,
  %E0R
  sign(B,sign(A,pair(player(B),
    pair(player(S),
      pair(hash(enc(x,itm(y))),
        enc(ttp,pair(keym(x),
          player(A))))))))) ,A) + tau).

```

```

(recv(A,keym(x),B).
evidence_Bob(x,y).
send(B,sign(B,pair(player(A),
pair(hash(pair(itm(y),keym(x))),keym(x)))),A) +
(%send resolve request
send(B,sign(B,sign(A,pair(player(B),
pair(player(S),
pair(hash(enc(x,itm(y))),
enc(ttp,pair(keym(x),
player(A))))))),S).

%session aborted
(recv(S,
sign(S,
pair(player(A),
pair(player(B),
pair(hash(enc(x,itm(y))),
enc(ttp,
pair(keym(x),
player(A))))))),
B) +
%we get evidence
recv(S,sign(S,pair(player(A),
pair(player(B),
pair(keym(x),hash(enc(x,itm(y))))))),B).
evidence_Bob(x,y))).
terminate_Bob(x,y).Bob))

Sam(Ss:Knowledge)=
%resolve request
sum(qq:Player,sum(p:Player,sum(q:Player,sum(y:Item,sum(x:Key,
(recv(qq,sign(q,sign(p,pair(player(q),
pair(player(S),
pair(hash(enc(x,itm(y))),
enc(ttp,pair(keym(x),
player(p))))))),S).
(send(S,sign(S,pair(player(p),
pair(player(q),
pair(hash(enc(x,itm(y))),
enc(ttp,pair(keym(x),
player(p))))))),qq).Sam(Ss)
<|in(pair(boolm(F),
pair(pair(player(p),player(q)),pair(itm(y),keym(x))))),Ss)|>
send(S,sign(S,pair(player(p),
pair(player(q),
pair(keym(x),hash(enc(x,itm(y))))))),qq).
Sam(add(pair(boolm(T),
pair(pair(player(p),player(q)),pair(itm(y),keym(x))))),
Ss)))) +
%abort request
recv(A,sign(A,pair(boolm(F),
pair(hash(enc(x,itm(y))),

```

```

pair(player(B),
    enc(ttp,pair(keym(x),player(A))))),S).
(send(S,sign(S,pair(player(A),
    pair(player(B),
        pair(keym(x),hash(enc(x,itm(y)))))),A).
    Sam(Ss)
    <|in(pair(boolm(T),
        pair(pair(player(A),player(B)),pair(itm(y),keym(x))))),Ss)|>
    abort(x,y).send(S,sign(S,pair(player(A),
        pair(player(B),
            pair(hash(enc(x,itm(y))),
                enc(ttp,pair(keym(x),
                    player(A)))))),A).
    Sam(add(pair(boolm(F),
        pair(pair(player(A),player(B)),pair(itm(y),keym(x))),
            Ss))))))

Alice(x:Key)=
    delta<|eq(x,ttp)|>
sum(y:Item,
    send(A,pair(enc(x,itm(y)),
        sign(A,pair(player(B),
            pair(player(S),
                pair(hash(enc(x,itm(y))),
                    enc(ttp,pair(keym(x),player(A))))))),B).
    init_Alice(x,y).
    (%Bob replies - continue
    recv(B,sign(B,sign(A,pair(player(B),
        pair(player(S),
            pair(hash(enc(x,itm(y))),
                enc(ttp,pair(keym(x),
                    player(A))))))),A).
    (
    send(A,keym(x),B).
    %Bob plays well
    recv(B,sign(B,pair(player(A),pair(hash(pair(itm(y),keym(x))),keym(x))))),A).
    evidence_Alice(x,y) +
    %Bob doesnt play well - resolve
    send(A,sign(B,sign(A,pair(player(B),
        pair(player(S),
            pair(hash(enc(x,itm(y))),
                enc(ttp,pair(keym(x),
                    player(A))))))),S).
    (%was aborted
    recv(S,sign(S,pair(player(A),
        pair(player(B),
            pair(hash(enc(x,itm(y))),
                enc(ttp,pair(keym(x),player(A)))))),A) +
    %resolved
    recv(S,sign(S,pair(player(A),
        pair(player(B),pair(keym(x),hash(enc(x,itm(y)))))),A).

```

```

        evidence_Alice(x,y).terminate_Alice(x,y)))

+
%Bob doesnt reply - abort
send(A,sign(A,pair(boolm(F),
                    pair(hash(enc(x,itm(y))),
                        pair(player(B),
                            enc(ttp,pair(keym(x),player(A))))))),S).

(% abort ok
recv(S,sign(S,pair(player(A),
                    pair(player(B),
                        pair(hash(enc(x,itm(y))),
                            enc(ttp,pair(keym(x),player(A))))))),A) +

% already resolved, we get evidence
(recv(S,sign(S,pair(player(A),
                    pair(player(B),
                        pair(keym(x),hash(enc(x,itm(y))))))),A) .
    evidence_Alice(x,y))).terminate_Alice(x,y)).Alice(nxt(x))

init    encap({send,recv},
             Bob||
             Alice(zero)||
             Sam(emptyset))

```

A.2 Malicious Alice, Honest Bob, Checking Safety

In this section some parts of the definitions of abstract data types will be omitted, because they are exactly the same as what appeared in section A.1. In order to complete this code, it is enough to copy the abstract data type definitions missing here from section A.1.

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Key Data Type
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sort    Key
func    zero :-> Key
        one :-> Key
        ttp :-> Key
map     eq:Key#Key->Bool
        leq:Key#Key->Bool
        nxt:Key->Key
var     k1,k2: Key
rew     leq(k1,k1)=T
        leq(zero,k1)=T
        leq(one,zero)=F      leq(one,ttp)=T
        leq(ttp,zero)=F      leq(ttp,one)=F
        eq(k1,k2)=and(leq(k1,k2),leq(k2,k1))
        nxt(zero)=one
        nxt(one)=ttp

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Declaration of Processes
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

act      send,recv,com,comX,comY:Player#Message#Player
        init_Bob:Key#Item
        evidence_Bob:Key#Item
evidence_Alice:Key#Item
        terminate_Bob:Key#Item

comm      send|recv=com
proc

Bob=sum(x:Key,sum(y:Item,sum(xxx:Key,
    recv(A,pair(enc(x,itm(y))),
        %E00
        sign(A,pair(player(B),
            pair(player(S),
                pair(hash(enc(x,itm(y))),
                    enc(ttp,pair(keym(xxx),
                        player(A))))))),B).

init_Bob(x,y).
(send(B,
    %E0R
    sign(B,sign(A,pair(player(B),
        pair(player(S),
            pair(hash(enc(x,itm(y))),
                enc(ttp,pair(keym(xxx),
                    player(A))))))),A) + tau).

(recv(A,keym(x),B).
evidence_Bob(x,y).
send(B,sign(B,pair(player(A),
    pair(hash(pair(itm(y),keym(x)),keym(x))),A) +
(%send resolve request
send(B,sign(B,sign(A,pair(player(B),
    pair(player(S),
        pair(hash(enc(x,itm(y))),
            enc(ttp,pair(keym(xxx),
                player(A))))))),A).

%session aborted
(recv(A,
    sign(S,
        pair(player(A),
            pair(player(B),
                pair(hash(enc(x,itm(y))),
                    enc(ttp,
                        pair(keym(x),
                            player(A))))))),
        B) + %.evidence_Bob(x,y) +
%we get evidence
recv(A,sign(S,pair(player(A),
    pair(player(B),
        pair(keym(x),hash(enc(x,itm(y)))))),B).
    evidence_Bob(x,y)))
<|eq(xxx,x)|>tau)).terminate_Bob(x,y).Bob))

```

```

Sam(Ss:Knowledge)=
  %resolve request
  sum(p:Player, sum(q:Player, sum(y:Item, sum(x:Key, sum(xxx:Key,
    (recv(A, sign(q, sign(p, pair(player(q),
      pair(player(S),
        pair(hash(enc(x, itm(y))),
          enc(ttp, pair(keym(xxx),
            player(p))))))))), S).

    (send(S, sign(S, pair(player(p),
      pair(player(q),
        pair(hash(enc(x, itm(y))),
          enc(ttp, pair(keym(xxx),
            player(p))))))))), A). Sam(Ss)

    <| in(pair(boolm(F),
      pair(pair(player(p), player(q)), pair(itm(y), keym(x))))), Ss) |>
    send(S, sign(S, pair(player(p),
      pair(player(q),
        pair(keym(xxx), hash(enc(x, itm(y))))))), A).

    Sam(add(pair(boolm(T),
      pair(pair(player(p), player(q)), pair(itm(y), keym(x)))),
      Ss))) +
    %abort request
    recv(A, sign(p, pair(boolm(F),
      pair(hash(enc(x, itm(y))),
        pair(player(q),
          enc(ttp, pair(keym(xxx), player(p))))))), S).

    (send(S, sign(S, pair(player(p),
      pair(player(q),
        pair(keym(xxx), hash(enc(x, itm(y))))))), A).

    Sam(Ss)
    <| in(pair(boolm(T),
      pair(pair(player(p), player(q)), pair(itm(y), keym(x))))), Ss) |>
    send(S, sign(S, pair(player(p),
      pair(player(q),
        pair(hash(enc(x, itm(y))),
          enc(ttp, pair(keym(xxx),
            player(p))))))), A).

    Sam(add(pair(boolm(F),
      pair(pair(player(p), player(q)), pair(itm(y), keym(x)))),
      Ss))))))
    <| and(not(eq(p, q)), and(not(eq(p, S)), not(eq(q, S)))) |> delta))
    %))) <| not(eq(p, q)) |> delta))

Intruder(X:Knowledge, Z:Bool)=
  sum(p:Player, sum(m:Message,
    recv(p, m, A). Intruder(refresh(A, union(A, decomp(A, m), X)), Z))) +
  sum(m:Message, sum(p:Player,
    send(A, m, p). Intruder(X, Z) <| synth(A, m, X) |> delta)) +

```



```

sum(x:Key, sum(y:Item,
  evidence_Alice(x,y).Intruder(X,F)
  <|synth(A,pair(sign(B,sign(A,pair(player(B),
    pair(player(S),
      pair(hash(pair(itm(y),
        keym(x))),
          enc(ttp,
            pair(keym(x),
              player(A))))))))),
    sign(B,pair(player(A),
      pair(hash(pair(itm(y),keym(x))),
        keym(x))))),X)|>delta))

  <|eq(Z,T)|>delta +
sum(x:Key, sum(y:Item,
  evidence_Alice(x,y).Intruder(X,F)
  <|synth(A,pair(sign(B,sign(A,pair(player(B),
    pair(player(S),
      pair(hash(pair(itm(y),
        keym(x))),
          enc(ttp,
            pair(keym(x),
              player(A))))))))),
    sign(S,pair(player(A),
      pair(player(B),
        pair(keym(x),
          hash(pair(itm(y),keym(x))))))))),X)|>
delta))<|eq(Z,T)|>delta

init      encap({send,recv},
           Bob||
           Intruder(set(keym(zero),emptset),T)||
           Sam(emptset))

```

A.3 Malicious Bob, Honest Alice, Checking Safety

In this section some parts of the definitions of abstract data types will be omitted, because they are exactly the same as what appeared in section A.1. In order to complete this code, it is enough to copy the abstract data type definitions missing here from section A.1.

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Key Data Type
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sort      Key
func      zero :-> Key
          one :-> Key
          ttp :-> Key
map       eq:Key#Key->Bool
          leq:Key#Key->Bool
          nxt:Key->Key
var       k1,k2: Key
rew       leq(k1,k1)=T
          leq(zero,k1)=T

```

```

leq(one,zero)=F          leq(one,ttp)=T
leq(ttp,zero)=F          leq(ttp,one)=F

eq(k1,k2)=and(leq(k1,k2),leq(k2,k1))

nxt(zero)=one
nxt(one)=ttp

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Declaration of Processes
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
act      send,recv,com,comX,comY:Player#Message#Player

        evidence_Alice:Key#Item
        evidence_Bob:Key#Item
        terminate_Alice:Key#Item
        init_Alice:Key#Item

comm

        send|recv=com

proc

Alice(x:Key)=
  delta
  <|eq(x,ttp)|>
  sum(y:Item,
    send(A,pair(enc(x,itm(y)),
      sign(A,pair(player(B),
        pair(player(S),
          pair(hash(enc(x,itm(y))),
            enc(ttp,pair(keym(x),player(A))))))),B).

    init_Alice(x,y).
    (%Bob replies - continue
    recv(B,sign(B,sign(A,pair(player(B),
      pair(player(S),
        pair(hash(enc(x,itm(y))),
          enc(ttp,pair(keym(x),
            player(A))))))),A).

    send(A,keym(x),B).
    (%Bob plays well
    recv(B,sign(B,pair(player(A),pair(hash(pair(itm(y),keym(x))),keym(x))))),A).
    evidence_Alice(x,y) +
    %Bob doesnt play well - resolve
    send(A,sign(B,sign(A,pair(player(B),
      pair(player(S),
        pair(hash(enc(x,itm(y))),
          enc(ttp,pair(keym(x),
            player(A))))))),B).

    (%was aborted
    recv(B,sign(S,pair(player(A),
      pair(player(B),

```

```

pair(hash(enc(x,itm(y))),
      enc(ttp,pair(keym(x),player(A))))),A) +
%resolved
recv(B,sign(S,pair(player(A),
pair(player(B),pair(keym(x),hash(enc(x,itm(y)))))),A).
evidence_Alice(x,y))) +
%Bob doesnt reply - abort
send(A,sign(A,pair(boolm(F),
pair(hash(enc(x,itm(y))),
pair(player(B),
enc(ttp,pair(keym(x),player(A)))))),B).
(% abort ok
recv(B,sign(S,pair(player(A),
pair(player(B),
pair(hash(enc(x,itm(y))),
enc(ttp,pair(keym(x),player(A)))))),A) +
% already resolved, we get evidence
(recv(B,sign(S,pair(player(A),
pair(player(B),
pair(keym(x),hash(enc(x,itm(y)))))),A).
evidence_Alice(x,y))).terminate_Alice(x,y)).Alice(nxt(x))

Sam(Ss:Knowledge)=
%resolve request
sum(p:Player,sum(q:Player,sum(y:Item,sum(x:Key,sum(xxx:Key,
(recv(B,sign(q,sign(p,pair(player(q),
pair(player(S),
pair(hash(enc(x,itm(y))),
enc(ttp,pair(keym(xxx),
player(p))))))),S).
(send(S,sign(S,pair(player(p),
pair(player(q),
pair(hash(enc(x,itm(y))),
enc(ttp,pair(keym(xxx),player(p))))))),B).
Sam(Ss)
<|in(pair(boolm(F),
pair(pair(player(p),player(q)),pair(itm(y),keym(x))),Ss)|>
send(S,sign(S,pair(player(p),
pair(player(q),
pair(keym(xxx),hash(enc(x,itm(y))))))),B).
Sam(add(pair(boolm(T),
pair(pair(player(p),player(q)),pair(itm(y),keym(x))),Ss))) +
%abort request
recv(B,sign(p,pair(boolm(F),
pair(hash(enc(x,itm(y))),
pair(player(q),
enc(ttp,pair(keym(xxx),player(p))))))),S).
(send(S,sign(S,pair(player(p),
pair(player(q),
pair(keym(xxx),hash(enc(x,itm(y))))))),B).

```

```

Sam(Ss)
<| in(pair(boolm(T),
    pair(pair(player(p),player(q)),pair(itm(y),keym(x))))),Ss)|>
send(S,sign(S,pair(player(p),
    pair(player(q),
        pair(hash(enc(x,itm(y))),
            enc(ttp,pair(keym(xxx),player(p))))))),B).

Sam(add(pair(boolm(F),
    pair(pair(player(p),player(q)),pair(itm(y),keym(x)))),
    Ss))))))
<| and(not(eq(p,q)),and(not(eq(p,S)),not(eq(q,S))))|>delta))
%))<| not(eq(p,q))|>delta))

Intruder(X:Knowledge,Z:Bool)=
    sum(p:Player,sum(m:Message,
        recv(p,m,B).Intruder(refresh(B,union(B,decomp(B,m),X)),Z)
        )) +
    sum(m:Message, sum(p:Player,
        send(B,m,p).Intruder(X,Z)<| synth(B,m,X)|>delta)) +
    sum(x:Key, sum(y:Item,
        evidence_Bob(x,y).Intruder(X,F)
        <| synth(B,pair(sign(A,pair(player(B),
            pair(player(S),
                pair(hash(enc(x,itm(y))),
                    enc(ttp,pair(keym(x),player(A))))))),
            pair(enc(x,itm(y)),keym(x))),X)|>delta))
        <| eq(Z,T)|>delta

init    encap({send,recv},
    Alice(zero)||Intruder(emptyset,T)||Sam(emptyset))

```

A.4 Malicious Alice, Honest Bob, Checking Termination

In this section some parts of the definitions of abstract data types will be omitted, because they are exactly the same as what appeared in section A.1. In order to complete this code, it is enough to copy the abstract data type definitions missing here from section A.1.

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Key Data Type
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sort    Key
func    zero :-> Key
        one :-> Key
        ttp :-> Key
map     eq:Key#Key->Bool
        leq:Key#Key->Bool
        nxt:Key->Key
var     k1,k2: Key
rew     leq(k1,k1)=T
        leq(zero,k1)=T

```

```

leq(one,zero)=F          leq(one,ttp)=T
leq(ttp,zero)=F          leq(ttp,one)=F

eq(k1,k2)=and(leq(k1,k2),leq(k2,k1))

nxt(zero)=one
nxt(one)=ttp

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Declaration of Processes
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
act      sendX,sendY,send,recv,com,comX,comY:Player#Message#Player
        init_Bob:Key#Item
evidence_Bob:Key#Item
terminate_Bob:Key#Item

comm      sendX|recv=comX
          sendY|recv=comY
          send|recv=com

proc

Bob=sum(x:Key,sum(y:Item,sum(xxx:Key,
    recv(A,pair(enc(x,itm(y)),
        %E00
        sign(A,pair(player(B),
            pair(player(S),
                pair(hash(enc(x,itm(y))),
                    enc(ttp,pair(keym(xxx),
                        player(A))))))),B).

init_Bob(x,y).
(send(B,
    %EOR
    sign(B,sign(A,pair(player(B),
        pair(player(S),
            pair(hash(enc(x,itm(y))),
                enc(ttp,pair(keym(xxx),
                    player(A))))))),A) + tau).

(recv(A,keym(x),B).
evidence_Bob(x,y).
send(B,sign(B,pair(player(A),
    pair(hash(pair(itm(y),keym(x))),keym(x))),A) +
(%send resolve request
send(B,sign(B,sign(A,pair(player(B),
    pair(player(S),
        pair(hash(enc(x,itm(y))),
            enc(ttp,pair(keym(xxx),
                player(A))))))),A).

%session aborted
(recv(A,
    sign(S,
        pair(player(A),
            pair(player(B),

```

```

        pair(hash(enc(x,itm(y))),
              enc(ttp,
                  pair(keym(x),
                      player(A))))),
    B) + %.evidence_Bob(x,y) +
%we get evidence
recv(A,sign(S,pair(player(A),
                    pair(player(B),
                        pair(keym(x),hash(enc(x,itm(y)))))),B).
    evidence_Bob(x,y))
<|eq(xxx,x)|>tau)).terminate_Bob(x,y).Bob))

Sam(Ss:Knowledge)=
%resolve request
sum(p:Player,sum(q:Player,sum(y:Item,sum(x:Key,sum(xxx:Key,
    (recv(A,sign(q,sign(p,pair(player(q),
        pair(player(S),
            pair(hash(enc(x,itm(y))),
                enc(ttp,pair(keym(xxx),
                    player(p))))))),S).
    (send(S,sign(S,pair(player(p),
        pair(player(q),
            pair(hash(enc(x,itm(y))),
                enc(ttp,pair(keym(xxx),
                    player(p))))))),A).Sam(Ss)
    <|in(pair(boolm(F),
        pair(pair(player(p),player(q)),pair(itm(y),keym(x))))),Ss)|>
    send(S,sign(S,pair(player(p),
        pair(player(q),
            pair(keym(xxx),hash(enc(x,itm(y)))))),A).
    Sam(add(pair(boolm(T),
        pair(pair(player(p),player(q)),pair(itm(y),keym(x))),
            Ss))) +
%abort request
recv(A,sign(p,pair(boolm(F),
    pair(hash(enc(x,itm(y))),
        pair(player(q),
            enc(ttp,pair(keym(xxx),player(p))))))),S).
    (send(S,sign(S,pair(player(p),
        pair(player(q),
            pair(keym(xxx),hash(enc(x,itm(y)))))),A).
    Sam(Ss)
    <|in(pair(boolm(T),
        pair(pair(player(p),player(q)),pair(itm(y),keym(x))))),Ss)|>
    send(S,sign(S,pair(player(p),
        pair(player(q),
            pair(hash(enc(x,itm(y))),
                enc(ttp,pair(keym(xxx),
                    player(p))))))),A).
    Sam(add(pair(boolm(F),
        pair(pair(player(p),player(q)),pair(itm(y),keym(x))),

```

```

        Ss))))))
    <|and(not(eq(p,q)),and(not(eq(p,S)),not(eq(q,S))))|>delta))
%))<|not(eq(p,q))|>delta))

% Y is modeled as a set, not a multi-set

Intruder(X:Knowledge,Y: Knowledge)=
    sum(p:Player,sum(m:Message,
        recv(p,m,A).Intruder(refresh(A,union(A,decomp(A,m),X)),add(m,Y)))) +
    sum(m:Message, sum(p:Player,
        sendX(A,m,p).Intruder(X,Y)<|and(synth(A,m,X),not(in(m,Y)))|>delta)) +
    sum(m:Message,sum(p:Player,
        sendY(A,m,p)).Intruder(X,rem(m,Y))<|in(m,Y)|>delta))

init    encap({send,recv,sendX,sendY},
           Bob||
           Intruder(set(keym(zero),emptset),emptset)||
           Sam(emptset))

```

A.5 Malicious Bob, Honest Alice, Checking Safety

In this section some parts of the definitions of abstract data types will be omitted, because they are exactly the same as what appeared in section A.1. In order to complete this code, it is enough to copy the abstract data type definitions missing here from section A.1.

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Key Data Type
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sort    Key
func     zero :-> Key
         one :-> Key
         ttp :-> Key
map      eq:Key#Key->Bool
         leq:Key#Key->Bool
         nxt:Key->Key
var      k1,k2: Key
rew      leq(k1,k1)=T
         leq(zero,k1)=T
         leq(one,zero)=F      leq(one,ttp)=T
         leq(ttp,zero)=F      leq(ttp,one)=F

         eq(k1,k2)=and(leq(k1,k2),leq(k2,k1))

         nxt(zero)=one
         nxt(one)=ttp

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Declaration of Processes
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
act      sendX,sendY,send,recv,com,comX,comY:Player#Message#Player

```

```

evidence_Alice:Key#Item
terminate_Alice:Key#Item
init_Alice:Key#Item

comm    sendX|recv=comX
        sendY|recv=comY
        send|recv=com

proc

Alice(x:Key)=
  delta
  <|eq(x,ttp)|>
  sum(y:Item,
    send(A,pair(enc(x,itm(y)),
      sign(A,pair(player(B),
        pair(player(S),
          pair(hash(enc(x,itm(y))),
            enc(ttp,pair(keym(x),player(A))))))),B).

  init_Alice(x,y).
  (%Bob replies - continue
    recv(B,sign(B,sign(A,pair(player(B),
      pair(player(S),
        pair(hash(enc(x,itm(y))),
          enc(ttp,pair(keym(x),
            player(A))))))),A).

    send(A,keym(x),B).
  (%Bob plays well
    recv(B,sign(B,pair(player(A),pair(hash(pair(itm(y),keym(x))),keym(x))))),A).
    evidence_Alice(x,y) +
  %Bob doesnt play well - resolve
    send(A,sign(B,sign(A,pair(player(B),
      pair(player(S),
        pair(hash(enc(x,itm(y))),
          enc(ttp,pair(keym(x),
            player(A))))))),B).

  (%was aborted
    recv(B,sign(S,pair(player(A),
      pair(player(B),
        pair(hash(enc(x,itm(y))),
          enc(ttp,pair(keym(x),player(A))))))),A) +

  %resolved
    recv(B,sign(S,pair(player(A),
      pair(player(B),pair(keym(x),hash(enc(x,itm(y))))))),A).
    evidence_Alice(x,y)) +
  %Bob doesnt reply - abort
    send(A,sign(A,pair(boolm(F),
      pair(hash(enc(x,itm(y))),
        pair(player(B),
          enc(ttp,pair(keym(x),player(A))))))),B).

  (% abort ok
    recv(B,sign(S,pair(player(A),

```



```

        pair(player(B),
            pair(hash(enc(x,itm(y))),
                enc(ttp,pair(keym(x),player(A)))))),A) +
% already resolved, we get evidence
(recv(B,sign(S,pair(player(A),
    pair(player(B),
        pair(keym(x),hash(enc(x,itm(y)))))),A).
    evidence_Alice(x,y))).terminate_Alice(x,y)).Alice(nxt(x))

Sam(Ss:Knowledge)=
    %resolve request
    sum(p:Player,sum(q:Player,sum(y:Item,sum(x:Key,sum(xxx:Key,
        (recv(B,sign(q,sign(p,pair(player(q),
            pair(player(S),
                pair(hash(enc(x,itm(y))),
                    enc(ttp,pair(keym(xxx),
                        player(p))))))),S).
            (send(S,sign(S,pair(player(p),
                pair(player(q),
                    pair(hash(enc(x,itm(y))),
                        enc(ttp,pair(keym(xxx),player(p))))))),B).

    Sam(Ss)
    <|in(pair(boolm(F),
        pair(pair(player(p),player(q)),pair(itm(y),keym(x))),Ss)|>
    send(S,sign(S,pair(player(p),
        pair(player(q),
            pair(keym(xxx),hash(enc(x,itm(y))))))),B).

    Sam(add(pair(boolm(T),
        pair(pair(player(p),player(q)),pair(itm(y),keym(x))),Ss))) +
%abort request
    recv(B,sign(p,pair(boolm(F),
        pair(hash(enc(x,itm(y))),
            pair(player(q),
                enc(ttp,pair(keym(xxx),player(p))))))),S).
    (send(S,sign(S,pair(player(p),
        pair(player(q),
            pair(keym(xxx),hash(enc(x,itm(y))))))),B).

    Sam(Ss)
    <|in(pair(boolm(T),
        pair(pair(player(p),player(q)),pair(itm(y),keym(x))),Ss)|>
    send(S,sign(S,pair(player(p),
        pair(player(q),
            pair(hash(enc(x,itm(y))),
                enc(ttp,pair(keym(xxx),player(p))))))),B).

    Sam(add(pair(boolm(F),
        pair(pair(player(p),player(q)),pair(itm(y),keym(x))),
            Ss))))))
    <|and(not(eq(p,q)),and(not(eq(p,S)),not(eq(q,S))))|>delta))
%)))<|not(eq(p,q))|>delta))

```

```

% Y is modeled as a set, not a multi-set

Intruder(X:Knowledge,Y: Knowledge)=
  sum(p:Player,sum(m:Message,
    recv(p,m,B).Intruder(refresh(B,union(B,decomp(B,m),X)),add(m,Y)) )) +
  sum(m:Message, sum(p:Player,
    sendX(B,m,p).Intruder(X,Y)<|and(synth(B,m,X),not(in(m,Y)))|>delta)) +

  sum(m:Message,sum(p:Player,
    sendY(B,m,p).Intruder(X,rem(m,Y))<|in(m,Y)|>delta)

init      encap({send,recv,sendX,sendY},
              Alice(zero)||Intruder(emptyset,emptyset)||Sam(emptyset))

```

B Further Experiments

B.1 Malicious Bob, Honest Alice, Checking Safety, Key Reuse Experiment

In this section some parts of the definitions of abstract data types will be omitted, because they are exactly the same as what appeared in section A.1. In order to complete this code, it is enough to copy the abstract data type definitions missing here from section A.1.

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Item Data Type.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sort      Item
func d1: -> Item
d2: -> Item
map      eq: Item # Item -> Bool
         leq: Item # Item -> Bool
var      d,d': Item
rew      leq(d,d)=T
         leq(d1,d)=T
         leq(d2,d1)=F

         eq(d,d')=and(leq(d,d'),leq(d',d))

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Declaration of Processes
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
act      sendX,sendY,send,recv,com,comX,comY:Player#Message#Player

         evidence_Alice:Key#Item
         evidence_Bob:Key#Item
         terminate_Alice:Key#Item
         init_Alice:Key#Item
         terminate_Bob:Key#Item

```

```

comm    sendX|recv=comX
        sendY|recv=comY
        send|recv=com

proc

Alice(y:Item)=
    send(A,pair(enc(zero,itm(y)),
                sign(A,pair(player(B),
                            pair(player(S),
                                pair(hash(enc(zero,itm(y))),
                                    enc(ttp,pair(keym(zero),player(A))))))))) ,B).

    init_Alice(zero,y).
    (%Bob replies - continue
    recv(B,sign(B,sign(A,pair(player(B),
                            pair(player(S),
                                pair(hash(enc(zero,itm(y))),
                                    enc(ttp,pair(keym(zero),
                                                player(A))))))))) ,A).

    send(A,keym(zero),B).
    (%Bob plays well
    recv(B,sign(B,pair(player(A),pair(hash(pair(itm(y),keym(zero))),keym(zero)))) ,A).
    evidence_Alice(zero,y) +
    %Bob doesnt play well - resolve
    send(A,sign(B,sign(A,pair(player(B),
                            pair(player(S),
                                pair(hash(enc(zero,itm(y))),
                                    enc(ttp,pair(keym(zero),
                                                player(A))))))))) ,B).

    (%was aborted
    recv(B,sign(S,pair(player(A),
                            pair(player(B),
                                pair(hash(enc(zero,itm(y))),
                                    enc(ttp,pair(keym(zero),player(A))))))))) ,A) +

    %resolved
    recv(B,sign(S,pair(player(A),
                            pair(player(B),pair(keym(zero),hash(enc(zero,itm(y))))))))) ,A).
    evidence_Alice(zero,y))) +
    %Bob doesnt reply - abort
    send(A,sign(A,pair(boolm(F),
                    pair(hash(enc(zero,itm(y))),
                        pair(player(B),
                            enc(ttp,pair(keym(zero),player(A))))))))) ,B).

    (% abort ok
    recv(B,sign(S,pair(player(A),
                            pair(player(B),
                                pair(hash(enc(zero,itm(y))),
                                    enc(ttp,pair(keym(zero),player(A))))))))) ,A) +

    % already resolved, we get evidence
    (recv(B,sign(S,pair(player(A),
                            pair(player(B),
                                pair(keym(zero),hash(enc(zero,itm(y))))))))) ,A).

```

```

evidence_Alice(zero,y)))) .terminate_Alice(zero,y) .Alice(d2)

Sam(Ss:Knowledge)=
  %resolve request
  sum(p:Player, sum(q:Player, sum(y:Item, sum(x:Key, sum(xxx:Key,
    (recv(B, sign(q, sign(p, pair(player(q),
      pair(player(S),
        pair(hash(enc(x, itm(y))),
          enc(ttp, pair(keym(xxx),
            player(p))))))))), S).
    (send(S, sign(S, pair(player(p),
      pair(player(q),
        pair(hash(enc(x, itm(y))),
          enc(ttp, pair(keym(xxx), player(p))))))), B).
    Sam(Ss)
    <| in(pair(boolm(F),
      pair(pair(player(p), player(q)), pair(itm(y), keym(x))))), Ss) |>
    send(S, sign(S, pair(player(p),
      pair(player(q),
        pair(keym(xxx), hash(enc(x, itm(y))))))), B).
    Sam(add(pair(boolm(T),
      pair(pair(player(p), player(q)), pair(itm(y), keym(x))))), Ss))) +
  %abort request
  recv(B, sign(p, pair(boolm(F),
    pair(hash(enc(x, itm(y))),
      pair(player(q),
        enc(ttp, pair(keym(xxx), player(p))))))), S).
    (send(S, sign(S, pair(player(p),
      pair(player(q),
        pair(keym(xxx), hash(enc(x, itm(y))))))), B).
    Sam(Ss)
    <| in(pair(boolm(T),
      pair(pair(player(p), player(q)), pair(itm(y), keym(x))))), Ss) |>
    send(S, sign(S, pair(player(p),
      pair(player(q),
        pair(hash(enc(x, itm(y))),
          enc(ttp, pair(keym(xxx), player(p))))))), B).
    Sam(add(pair(boolm(F),
      pair(pair(player(p), player(q)), pair(itm(y), keym(x))),
      Ss))))))
    <| and(not(eq(p, q)), and(not(eq(p, S)), not(eq(q, S)))) |> delta))
  %))) <| not(eq(p, q)) |> delta))

Intruder(X:Knowledge, Z:Bool)=
  sum(p:Player, sum(m:Message,
    recv(p, m, B). Intruder(refresh(B, union(B, decomp(B, m), X)), Z)
    )) +
  sum(m:Message, sum(p:Player,

```

```

send(B,m,p).Intruder(X,Z)<|synth(B,m,X)|>delta)) +

sum(x:Key, sum(y:Item,
  evidence_Bob(x,y).Intruder(X,F)
  <|synth(B,pair(sign(A,pair(player(B),
    pair(player(S),
      pair(hash(enc(x,itm(y))),
        enc(ttp,pair(keym(x),player(A)))))),
    pair(enc(x,itm(y)),keym(x))),X)|>delta))
  <|eq(Z,T)|>delta

init      encap({send,recv},
            Alice(d1)||Intruder(emptyset,T)||Sam(emptyset))

```

B.2 Malicious Alice, Honest Bob, Checking Safety, Missing Hash in EOO_M Experiment

In this section some parts of the definitions of abstract data types will be omitted, because they are exactly the same as what appeared in section A.1. In order to complete this code, it is enough to copy the abstract data type definitions missing here from section A.1.

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Key Data Type
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sort      Key
func      zero :-> Key
           one :-> Key
           ttp :-> Key
map       eq:Key#Key->Bool
           leq:Key#Key->Bool
           nxt:Key->Key
var       k1,k2: Key
rew       leq(k1,k1)=T
           leq(zero,k1)=T
           leq(one,zero)=F      leq(one,ttp)=T
           leq(ttp,zero)=F      leq(ttp,one)=F

           eq(k1,k2)=and(leq(k1,k2),leq(k2,k1))

           nxt(zero)=one
           nxt(one)=ttp

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Declaration of Processes
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
act       send,recv,com,comX,comY:Player#Message#Player
           init_Bob:Key#Item
           evidence_Alice,evidence_Bob:Key#Item
           terminate_Bob:Key#Item

comm

send|recv=com

```

```

proc

Bob=sum(x:Key,
delta <| eq(x,ttp)|>
sum(y:Item,sum(xxx:Key,
    recv(A,pair(enc(x,itm(y)),
        %E00
        sign(A,pair(player(B),
            pair(player(S),
                enc(ttp,pair(keym(xxx),
                    player(A)))))),B).

init_Bob(xxx,y).
(send(B,
    %E0R
    sign(B,sign(A,pair(player(B),
        pair(player(S),
            enc(ttp,pair(keym(xxx),
                player(A)))))),A) + tau).

(recv(A,keym(x),B).
evidence_Bob(xxx,y).
send(B,sign(B,pair(player(A),pair(player(B),keym(xxx))))),A) +
(%send resolve request
send(B,sign(B,sign(A,pair(player(B),
    pair(player(S),
        enc(ttp,pair(keym(xxx),
            player(A)))))),A).

%session aborted
(recv(A,
    sign(S,
        pair(player(A),
            pair(player(B),
                enc(ttp,
                    pair(keym(xxx),
                        player(A))))), B)

%.evidence_Bob(x,y)
+
    %we get evidence
    recv(A,sign(S,pair(player(A),
        pair(player(B),
            keym(xxx)
))))),B).
    evidence_Bob(xxx,y)))
<|eq(xxx,x)|>tau).terminate_Bob(xxx,y).Bob)))

Sam(Ss:Knowledge)=
%resolve request
sum(p:Player,sum(q:Player,sum(xxx:Key,
    (recv(A,sign(q,sign(p,pair(player(q),
        pair(player(S),
            enc(ttp,pair(keym(xxx),
                player(p)))))),S).

```

```

(send(S,sign(S,pair(player(p),
                        pair(player(q),
                                enc(ttp,pair(keym(xxx),
                                                player(p)))))),A).Sam(Ss)
<|in(pair(boolm(F),
          pair(player(p),pair(player(q),keym(xxx))))),Ss)|>
send(S,sign(S,pair(player(p),
                    pair(player(q),
                            keym(xxx)
))),A).
Sam(add(pair(boolm(T),
            pair(player(p),pair(player(q),keym(xxx))))),
      Ss)) +
%abort request
recv(A,sign(p,pair(boolm(F),
                  pair(player(q),
                          enc(ttp,pair(keym(xxx),player(p)))))),S).
(send(S,sign(S,pair(player(p),
                    pair(player(q),
                            keym(xxx)
))),A).
Sam(Ss)
<|in(pair(boolm(T),
          pair(player(p),pair(player(q),keym(xxx))))),Ss)|>
send(S,sign(S,pair(player(p),
                    pair(player(q),
                            enc(ttp,pair(keym(xxx),
                                                player(p)))))),A).
Sam(add(pair(boolm(F),
            pair(player(p),pair(player(q),keym(xxx))))),
      Ss))))
<|and(not(eq(p,q)),and(not(eq(p,S)),not(eq(q,S))))|>delta))

Intruder(X:Knowledge,Z:Bool)=
sum(p:Player, sum(m:Message,
  recv(p,m,A).Intruder(refresh(A,union(A,decomp(A,m),X)),Z))) +
sum(m:Message, sum(p:Player,
  send(A,m,p).Intruder(X,Z)<|synth(A,m,X)|>delta)) +
sum(x:Key, sum(y:Item,
  evidence_Alice(x,y).Intruder(X,F)
  <|synth(A,pair(sign(B,sign(A,pair(player(B),
                                pair(player(S),
                                        enc(ttp,
                                            pair(keym(x),
                                                player(A)))))),
                                sign(B,pair(player(A),pair(player(B),
                                                                keym(x))))),X)|>delta))
  <|eq(Z,T)|>delta +
sum(x:Key, sum(y:Item,
  evidence_Alice(x,y).Intruder(X,F)
  <|synth(A,pair(sign(B,sign(A,pair(player(B),

```

```

pair(player(S),
      enc(ttp,
          pair(keym(x),
              player(A))))),
sign(S,pair(player(A),
            pair(player(B),
                keym(x)
                ))),X)|>
delta))<|eq(Z,T)|>delta

init    encap({send,recv},
             Bob||
             Intruder(set(keym(zero),set(keym(one),emptset)),T)||
             Sam(emptset))

```

B.3 Malicious Alice, Honest Bob, Checking Safety, Missing A's Identity Experiment

In this section the definitions of abstract data types will be omitted, because it is exactly the same as what appeared in section A.1.

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Declaration of Processes
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
act      send,recv,com:Player#Message#Player
        init_Bob:Key#Item
        evidence_Bob:Key#Item
evidence_Alice:Key#Item
        terminate_Bob:Key#Item

comm      send|recv=com
proc

Bob=sum(x:Key,sum(y:Item,sum(xxx:Key,
    recv(A,pair(enc(x,itm(y)),
        %E00
        sign(A,pair(player(B),
            pair(player(S),
                pair(hash(enc(x,itm(y))),
                    enc(ttp,pair(keym(xxx),
                        player(A))))))),B).

init_Bob(x,y).
(send(B,
    %E0R
    sign(B,sign(A,pair(player(B),
        pair(player(S),
            pair(hash(enc(x,itm(y))),
                enc(ttp,pair(keym(xxx),
                    player(A))))))),A) + tau).

(recv(A,keym(x),B).

```



```

evidence_Bob(x,y).
send(B,sign(B, pair(hash(pair(itm(y),keym(x))),keym(x))),A) +
(%send resolve request
send(B,sign(B,sign(A,pair(player(B),
pair(player(S),
pair(hash(enc(x,itm(y))),
enc(ttp,pair(keym(xxx),
player(A))))))))) ,A).

%session aborted
(recv(A,
sign(S,
pair(player(A),
pair(player(B),
pair(hash(enc(x,itm(y))),
enc(ttp,
pair(keym(x),
player(A))))))),
B) + %.evidence_Bob(x,y) +
%we get evidence
recv(A,sign(S,pair(player(A),
pair(player(B),
pair(keym(x),hash(enc(x,itm(y))))))),B).
evidence_Bob(x,y))
<|eq(xxx,x)|>tau).terminate_Bob(x,y).Bob)))

```

```

Sam(Ss:Knowledge)=
%resolve request
sum(p:Player,sum(q:Player,sum(y:Item,sum(x:Key,sum(xxx:Key,
(recv(A,sign(q,sign(p,pair(player(q),
pair(player(S),
pair(hash(enc(x,itm(y))),
enc(ttp,pair(keym(xxx),
player(p))))))))) ,S).
(send(S,sign(S,pair(player(p),
pair(player(q),
pair(hash(enc(x,itm(y))),
enc(ttp,pair(keym(xxx),
player(p))))))))) ,A).Sam(Ss)
<|in(pair(boolm(F),
pair(pair(player(p),player(q)),pair(itm(y),keym(x))))),Ss)|>
send(S,sign(S,pair(player(p),
pair(player(q),
pair(keym(xxx),hash(enc(x,itm(y))))))),A).
Sam(add(pair(boolm(T),
pair(pair(player(p),player(q)),pair(itm(y),keym(x))),
Ss))) +
%abort request
recv(A,sign(p,pair(boolm(F),
pair(hash(enc(x,itm(y))),
pair(player(q),
enc(ttp,pair(keym(xxx),player(p))))))))) ,S).

```

```

(send(S,sign(S,pair(player(p),
                    pair(player(q),
                        pair(keym(xxx),hash(enc(x,itm(y))))))),A).
Sam(Ss)
<|in(pair(boolm(T),
        pair(pair(player(p),player(q)),pair(itm(y),keym(x)))),Ss)|>
send(S,sign(S,pair(player(p),
                    pair(player(q),
                        pair(hash(enc(x,itm(y))),
                            enc(ttp,pair(keym(xxx),
                                player(p))))))),A).

Sam(add(pair(boolm(F),
            pair(pair(player(p),player(q)),pair(itm(y),keym(x)))),
        Ss))))))
<|and(not(eq(p,q)),and(not(eq(p,S)),not(eq(q,S))))|>delta))
%))<|not(eq(p,q))|>delta))

```

```

Intruder(X:Knowledge,Z:Bool)=
  sum(p:Player,sum(m:Message,
    recv(p,m,A).Intruder(
refresh(A,union(A,decomp(A,m),X)),Z)
)) +

```

```

  sum(m:Message, sum(p:Player,
    send(A,m,p).Intruder(X,Z)<|synth(A,m,X)|>delta)) +

sum(x:Key, sum(y:Item,
  evidence_Alice(x,y).Intruder(X,F)
  <|synth(A,pair(sign(B,sign(A,pair(player(B),
                                pair(player(S),
                                    pair(hash(enc(x,itm(y))),
                                        enc(ttp,
                                            pair(keym(x),
                                                player(A))))))),
                                sign(B,
                                    pair(hash(pair(itm(y),keym(x))),
                                        keym(x))),X)|>delta))
  <|eq(Z,T)|>delta

```

```

init    encap({send,recv},
          Bob||
          Intruder(
refresh(A,union(A,decomp(A,sign(B,pair(hash(pair(itm(d1),keym(zero))),keym(zero))))),emptset.
,T)||
          Sam(emptset))

```

B.4 Malicious Alice, Honest Bob, Checking Safety, Missing A's Identity Experiment

In this section the definitions of abstract data types will be omitted, because it is exactly the same as what appeared in section A.1.

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Declaration of Processes
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
act      send,recv,com:Player#Message#Player
        init_Bob:Key#Item
        evidence_Bob:Key#Item
evidence_Alice:Key#Item
        terminate_Bob:Key#Item

comm      send|recv=com
proc

Bob=sum(x:Key,sum(y:Item,sum(xxx:Key,
    recv(A,pair(enc(x,itm(y)),
        %E00
        sign(A,pair(player(B),
            pair(player(S),
                pair(hash(enc(x,itm(y))),
                    enc(ttp,pair(keym(xxx),
                        player(A))))))),B).

    init_Bob(x,y).
    (send(B,
        %E0R
        sign(B,sign(A,pair(player(B),
            pair(player(S),
                pair(hash(enc(x,itm(y))),
                    enc(ttp,pair(keym(xxx),
                        player(A))))))),A) + tau).

    (recv(A,keym(x),B).
    evidence_Bob(x,y).
    send(B,sign(B, pair(player(A),keym(x))),A) +
    (%send resolve request
    send(B,sign(B,sign(A,pair(player(B),
        pair(player(S),
            pair(hash(enc(x,itm(y))),
                enc(ttp,pair(keym(xxx),
                    player(A))))))),A).

    %session aborted
    (recv(A,
        sign(S,
            pair(player(A),
                pair(player(B),
                    pair(hash(enc(x,itm(y))),
                        enc(ttp,
                            pair(keym(x),
                                player(A))))))),

```

```

        B) + %.evidence_Bob(x,y) +
%we get evidence
recv(A,sign(S,pair(player(A),
                    pair(player(B),
                    pair(keym(x),hash(enc(x,itm(y))))))),B).
    evidence_Bob(x,y)))
<|eq(xxx,x)|>tau).terminate_Bob(x,y).Bob)))

Sam(Ss:Knowledge)=
%resolve request
sum(p:Player,sum(q:Player,sum(y:Item,sum(x:Key,sum(xxx:Key,
    (recv(A,sign(q,sign(p,pair(player(q),
                    pair(player(S),
                    pair(hash(enc(x,itm(y))),
                    enc(ttp,pair(keym(xxx),
                    player(p))))))),S).
    (send(S,sign(S,pair(player(p),
                    pair(player(q),
                    pair(hash(enc(x,itm(y))),
                    enc(ttp,pair(keym(xxx),
                    player(p))))))),A).Sam(Ss)
    <|in(pair(boolm(F),
        pair(pair(player(p),player(q)),pair(itm(y),keym(x))))),Ss)|>
    send(S,sign(S,pair(player(p),
        pair(player(q),
        pair(keym(xxx),hash(enc(x,itm(y))))))),A).
    Sam(add(pair(boolm(T),
        pair(pair(player(p),player(q)),pair(itm(y),keym(x))),
        Ss))) +
    %abort request
    recv(A,sign(p,pair(boolm(F),
        pair(hash(enc(x,itm(y))),
        pair(player(q),
        enc(ttp,pair(keym(xxx),player(p))))))),S).
    (send(S,sign(S,pair(player(p),
        pair(player(q),
        pair(keym(xxx),hash(enc(x,itm(y))))))),A).
    Sam(Ss)
    <|in(pair(boolm(T),
        pair(pair(player(p),player(q)),pair(itm(y),keym(x))))),Ss)|>
    send(S,sign(S,pair(player(p),
        pair(player(q),
        pair(hash(enc(x,itm(y))),
        enc(ttp,pair(keym(xxx),
        player(p))))))),A).
    Sam(add(pair(boolm(F),
        pair(pair(player(p),player(q)),pair(itm(y),keym(x))),
        Ss))))))
    <|and(not(eq(p,q)),and(not(eq(p,S)),not(eq(q,S))))|>delta))
%)))<|not(eq(p,q))|>delta))

```

```

Intruder(X:Knowledge,Z:Bool)=
  sum(p:Player,sum(m:Message,
    recv(p,m,A).Intruder(
refresh(A,union(A,decomp(A,m),X)),Z)
)) +
  sum(m:Message, sum(p:Player,
    send(A,m,p).Intruder(X,Z)<|synth(A,m,X)|>delta)) +

sum(x:Key, sum(y:Item,
  evidence_Alice(x,y).Intruder(X,F)
  <|synth(A,pair(sign(B,sign(A,pair(player(B),
    pair(player(S),
      pair(hash(enc(x,itm(y))),
        enc(ttp,
          pair(keym(x),
            player(A))))))),
    sign(B,
      pair(player(A),
        keym(x))),X)|>delta))
  <|eq(Z,T)|>delta

init    encap({send,recv},
          Bob||
          Intruder(
refresh(A,union(A,decomp(A,sign(B,pair(player(A),keym(zero))))),emptset))
,T)||
          Sam(emptset))

```

C Properties

C.1 Fairness, Malicious Alice, Honest Bob

```

[(not("evidence_Bob(zero,d1)")*. "evidence_Alice(zero,d1)".
(not("evidence_Bob(zero,d1)")*. "terminate_Bob(zero,d1)"]false

```

C.2 Fairness, Malicious Bob, Honest Alice

```

[(not("evidence_Alice(zero,d1)")*. "evidence_Bob(zero,d1)".
(not("evidence_Alice(zero,d1)")*. "terminate_Alice(zero,d1)"]false

```

C.3 Timeliness, Malicious Alice, Honest Bob

```

[(not("evidence_Alice(zero,d1)")*. "terminate_Alice(zero,d1)".
(not("init_Alice(zero,d1)")*. "evidence_Bob(zero,d1)"]false

```

C.4 Timeliness, Malicious Bob, Honest Alice

```

[(not("evidence_Bob(zero,d1)")*. "terminate_Bob(zero,d1)".
(not("init_Bob(zero,d1)")*. "evidence_Alice(zero,d1)"]false

```

C.5 Termination, Malicious Alice, Honest Bob

```
[true*. "init_Bob(zero,d1)". (not("terminate_Bob(zero,d1)"))*]  
<(not('comX(.*,*,*)'))*. "terminate_Bob(zero,d1)">true
```

C.6 Termination, Malicious Bob, Honest Alice

```
[true*. "init_Alice(zero,d1)". (not("terminate_Alice(zero,d1)"))*]  
<(not('comX(.*,*,*)'))*. "terminate_Alice(zero,d1)">true
```

C.7 Effectiveness

```
[true*. "init_Alice(zero,d1)"]  
mu X. (<true>true and ([not("terminate_Alice(zero,d1)")]X))  
  
[(not("abort(zero,d1)" or "evidence_Alice(zero,d1)"))*.  
"terminate_Alice(zero,d1)"]false  
  
[true*. "init_Bob(zero,d1)"]  
mu X. (<true>true and ([not("terminate_Bob(zero,d1)")]X))  
  
[(not("abort(zero,d1)" or "evidence_Bob(zero,d1)"))*.  
"terminate_Bob(zero,d1)"]false
```

C.8 Fairness, Malicious Bob, Honest Alice, Key reuse experiment

```
[(not("evidence_Alice(zero,d2)"))*. "evidence_Bob(zero,d2)".  
(not("evidence_Alice(zero,d2)"))*. "terminate_Alice(zero,d2)"]false
```